Cooperative Spectrum Sensing with Diversity Reception in Cognitive Radios

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***Abstract*—Cognitive radio (CR) is a promising technology that is capable of exploiting the scarcity of radio spectrum. One of the most important challenges for a CR system is to perform spectrum sensing in a fading environment. Diversity reception techniques are often used to combat the detrimental effects of fading channels. In this paper, we derive representations for the average probabilities of detection and false alarm when using energy detection with different diversity reception schemes over Nakagami-m fading channels. These expressions are then proved to have lower computational complexity than those proposed in the literature. The performance of different diversity reception schemes is compared for finding a proper cooperative strategy under different constraints. Simulation results show that with the aid of channel state information (CSI), maximum ratio combining gives an upper bound of the detection performance. Without CSI, square-law combining offers the best detection performance.**

***Index Terms*—Cognitive radio, Spectrum sensing, Energy detection, Nakagami-m fading.**

I. Introduction

The radio frequency (RF) spectrum is currently managed by government agencies under an exclusive usage scheme. Due to the explosive development of wireless applications, it is evident that the available frequencies cannot meet the increasing demand. Interestingly, recent investigations reveal that there exists significant underutilisation of the allocated frequencies [1]. The spectral underutilisation can be solved by allowing a secondary user to access a licensed band when the primary user (PU) is absent. CR is widely agreed to be the most promising method for alleviating RF spectral scarcity. A crucial requirement of CRs is that they must rapidly fill in spectrum holes without posing harmful interference on PUs. This ability is dependent upon spectrum sensing, which is one of the most critical components in a CR system.

Energy detection [2] is commonly used in spectrum sensing, because it has a low implementation complexity and does not require channel state information (CSI) [3]. As fading occurs due to multipath propagation and shadowing, multiple CRs are often designed to collaborate in spectrum sensing. Previous work on cooperative spectrum sensing has shown that space diversity can increase the probability of detection (P_d) [4]–[7]. Using maximum ratio combining (MRC), selection combining (SC), square-law combining (SLC), and square-law selection (SLS) data fusion schemes, the performance of energy detection experiencing independent and identically distributed (i.i.d.) Rayleigh fading channels was researched in [8], [9]. Herath *et al.* studied the performance of MRC, SC, SLC, and SLS over multiple Nakagami-m fading channels in [10]–[12], respectively. Nonetheless, the result for MRC in [10] is numerically complicated, involving infinite sums, derivatives, and limit operations. The expressions of P_d for SLC and SLS in [12], and SC in [11] contain infinite sums of confluent Hypergeometric function, which therefore leads to a high computational complexity. In a distributed CR network, every CR behaves as both a sensing node and a fusion centre (FC). To satisfy a particular spectrum sensing requirement, CR requires to dynamically choose a detection threshold and calculate these probabilities due to the time-varying channel condition between the PU and CR (i.e. dynamically changing signal-to-noise ratio (SNR) and noise level). However, CR nodes may be battery-powered and have restricted computational resources. Therefore, a computationally inexpensive means of calculating these probabilities is advantageous. In addition, it is noteworthy that different diversity reception schemes will result in distinct performance. Hence, a comparison of these diversity reception schemes is of prime importance.

In this paper, we derive some expressions for the average probabilities of detection and false alarm when using energy detection with different diversity reception schemes over independent and identically distributed (i.i.d.) Nakagami-m fading channels. These expressions are then proved to have lower computational complexity than those proposed in literature. Finally, the performance of various diversity reception schemes is compared by simulations for finding a proper cooperative strategy under different constraints. The rest of this paper is organized as follows. Section II explains the system model. In Section III, we derive expressions for the average probability of detection using SLC, SLS, MRC,

The authors acknowledge the support of the UK Engineering and Physical Sciences Research Council (EPSRC) with Grant No. EP/I000054/1. J. Jiang, and C.-X. Wang acknowledge the support from the Scottish Funding Council for the Joint Research Institute in Signal and Image Processing between the University of Edinburgh and Heriot-Watt University, as part of the Edinburgh Research Partnership in Engineering and Mathematics (ERPem). C.-X. Wang also acknowledges the support of the RCUK for the "UK-China Science Bridges Project: R&D on (B)4G Wireless Mobile Communications" and the Opening Project of Key Laboratory of Cognitive Radio and Information Processing (Guilin University of Electronic Technology), Ministry of Education (No.: 2009K02).

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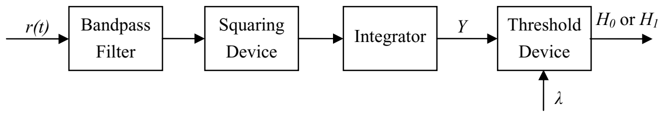

Fig. 1. Block diagram of the energy detector.

and SC diversity reception. Simulation results are presented in Section IV, with conclusions given in Section V.

II. System Model

At the energy detector, the received signal, $r(t)$, can be formulated as hypothesis test with H_0 (signal not present) or H_1 (signal present)

$$r(t) = \begin{cases} n(t), & H_0 \\ h(t)\ s(t) + n(t), & H_1 \end{cases} \tag{1}$$

where $h(t)$ denotes the complex channel gain between PUs and CRs, $s(t)$ denotes the transmitted signal from PUs, and $n(t)$ is AWGN.

In the system model shown in Fig. 1, the received signal at an energy detector will be filtered by an ideal bandpass filter with bandwidth W. Then using a magnitude squaring device, the received energy, Y, is measured over an observation time of T, and compared with a predetermined threshold, λ, to decide whether the signal is present or not. The test statistic, Y, can be modeled by central and non-central chi-square distributed random variables as [2]

$$Y \sim \begin{cases} \chi^2_{2u}, & H_0 \\ \chi^2_{2u}(2y), & H_1 \end{cases} \tag{2}$$

where "$\sim$" means "distributed as", y is SNR, and χ^2_{2u} and $\chi^2_{2u}(2y)$ denote the central and non-central chi-square distributions, respectively. Both distributions have the same degree of freedom (DoF), $2u$ ($u = TW$), and the latter one has a non-central parameter $2y$.

For an AWGN channel, if noise variance is assumed to be 1, the probabilities of false alarm and detection of the energy detector are given by [8]

$$P_f = P_r(Y > \lambda | H_0) = \frac{\Gamma(u, \lambda/2)}{\Gamma(u)} \tag{3}$$

$$P_d = P_r\,(Y > \lambda | H_1) = Q_u(\sqrt{2y}, \sqrt{\lambda}) \tag{4}$$

respectively, where $\Gamma(a)$ is the gamma function, $\Gamma(a, x)$ denotes the upper incomplete gamma function, and $Q_u(a, x)$ denotes the generalized Marcum Q-function given by

$$Q_u(a, x) = \frac{1}{a^{u-1}} \int_x^\infty t^u e^{-\frac{a^2+t^2}{2}} I_{u-1}(at)dt \tag{5}$$

where $I_v(a)$ is the v^{th} order modified Bessel function of the first kind.

In this paper, we use another form of generalized Marcum Q-function in (3) of [13] and represent P_d in (4) as

$$P_d(y, \lambda) = 1 - \sum_{n=0}^{\infty} \frac{\gamma(n+u, \frac{\lambda}{2})}{\Gamma(n+u)n!} y^n e^{-y} \tag{6}$$

where $\gamma(a, x)$ denotes the lower incomplete gamma function.

In a fading channel, the average probability of false alarm, $\overline{P_f}$, will remain the same as P_f in (3) [8]. In contrast, when the channel gain, $h(t)$, varies, the average probability of detection, $\overline{P_d}$, can be calculated by averaging P_d in (4) over all possible SNR values as [8]

$$\overline{P_d} = \int_0^\infty P_d(y, \lambda) f(y) dy \tag{7}$$

where $f(y)$ denotes the probability density function (PDF) of the SNR in a fading channel.

III. Spectrum Sensing over Multiple I.I.D. Nakagami-m Fading Channels

We will now analyze the spectrum sensing performance using different diversity reception techniques over multiple Nakagami-m fading channels. Since CR nodes are distributed in a large geographical area, the fading channels are assumed to be i.i.d.

A. Square-Law Combining

Using SLC, the squared and integrated energy vectors, $Y_1, Y_2, \cdots, Y_L$, are transmitted from multiple CRs to a FC, where the test statistic, $Y_{slc} = \sum_{i=1}^{L} Y_i$, is formed [9]. Thus, under H_0 hypothesis, if these L fading channels are i.i.d. and have the same noise variance, the test statistic, Y_{slc}, follows a central chi-square distribution with a $2Lu$ DoF. Under H_1 hypothesis, it follows a non-central chi-square distribution with a $2Lu$ DoF and non-central parameter of y_{slc} as below

$$Y_{slc} \sim \begin{cases} \chi^2_{2Lu}, & H_0 \\ \chi^2_{2Lu}(2y_{slc}), & H_1 \end{cases} \tag{8}$$

where $y_{slc} = \sum_{i=1}^{L} y_i$ for i.i.d. fading channels.

In the case of non-fading AWGN channels, using (4), (6) and (8), the probabilities of false alarm and detection under a SLC diversity scheme can be given as

$$P_{fa}^{slc} = \frac{\Gamma(Lu, \lambda/2)}{\Gamma(Lu)} \tag{9}$$

$$\begin{aligned} P_d^{slc} &= Q_{Lu}(\sqrt{2y_{slc}}, \sqrt{\lambda}), \\ &= 1 - \sum_{n=0}^{\infty} \frac{\gamma(n+Lu, \frac{\lambda}{2})}{\Gamma(n+Lu)n!} y_{slc}^n e^{-y_{slc}}. \end{aligned} \tag{10}$$

When the signal experiences fading over L channels, the average probability of false alarm will not change, and the average probability of detection can be evaluated by averaging P_d^{slc} in (10) over the combined SNR distribution as [8]

$$\overline{P_d^{slc}} = \int_0^\infty P_d^{slc}(y_{slc}, \lambda) f(y_{slc}) dy_{slc}, \quad y_{slc} > 0. \tag{11}$$

The PDF of the output SNR, y_{slc}, for L i.i.d. Nakagami-m fading channels is given by [14]

$$f(y_{slc}) = \frac{m^{Lm} y_{slc}^{Lm-1}}{\overline{y}^{Lm} \Gamma(Lm)} e^{-\frac{m}{\overline{y}} y_{slc}}, \quad y_{slc} > 0 \tag{12}$$

where $\overline{y}$ denotes the local-mean SNR, and m is the Nakagami-m fading factor ($m \in [1/2, \infty)$).

Substituting (10) and (12) into (11), we obtain

$$\overline{P_d^{slc}} = 1 - \frac{m^{Lm}}{\Gamma(Lm)\overline{y}^{Lm}} \sum_{n=0}^{\infty} \frac{\gamma(n+Lu, \frac{\lambda}{2})}{\Gamma(n+Lu)n!} \times \int_0^{\infty} y^{n+Lm-1} e^{-\frac{m+\overline{y}}{\overline{y}}y} dy. \quad (13)$$

Using (3.351-3) in [15] for calculating the integral in (13), we end up with

$$\overline{P_d^{slc}} = 1 - B(Lu, Lm, L\overline{y}) \quad (14)$$

where $B(\alpha, \beta, x)$ is defined by

$$B(\alpha, \beta, x) \triangleq \left(\frac{\beta}{\beta+x}\right)^{\beta} \sum_{n=0}^{\infty} \frac{\gamma(n+\alpha, \frac{\lambda}{2})(\beta)_n}{\Gamma(n+\alpha)n!} \left(\frac{x}{\beta+x}\right)^n \quad (15)$$

where $(a)_b = \frac{\Gamma(a+b)}{\Gamma(a)}$ denotes the Pochhammer Symbol.

B. Square-Law Selection

Using SLS, the FC only selects the branch with the largest energy, i.e., $Y_{sls} = \max(Y_1, Y_2, \cdots, Y_L)$. In the case of non-fading AWGN channels, the probabilities of false alarm and detection under a SLS diversity scheme is given by [9]

$$P_{fa}^{sls} = 1 - \left(1 - \frac{\Gamma(u, \lambda/2)}{\Gamma(u)}\right)^L \quad (16)$$

$$P_d^{sls} = 1 - \prod_{i=1}^{L} \left(1 - Q_u(\sqrt{2y_i}, \sqrt{\lambda})\right). \quad (17)$$

When there exists fading over L i.i.d. channels, the average probability of detection can be evaluated by averaging P_d^{sls} in (17) over all possible SNRs as

$$\overline{P_d^{sls}} = \int_0^{\infty} P_d^{sls}(y_i, \lambda) f(y_i) dy, \quad y_i > 0 \quad (18)$$

where $f(y_i)$ is given by,

$$f(y_i) = \frac{m^m y_i^{m-1}}{\overline{y_i}^m \Gamma(m)} e^{-\frac{m}{\overline{y_i}} y_i}, \quad y_i > 0 \quad (19)$$

where $\overline{y_i}$ denotes the local-mean SNR in the i-th node.

Substituting (17) and (19) into (18), we can obtain an expression for the average probability of detection. Since the channels are i.i.d., the average probability of detection can be calculated by

$$\overline{P_d^{sls}} = 1 - \prod_{i=1}^{L} B(u, m, \overline{y_i}). \quad (20)$$

In comparison with the results in [12], our results in (14) and (20) have lower computational complexity when u and m are integer multiples of $\frac{1}{24}$. This is because gamma function can be evaluated quickly using arithmetic-geometric mean iterations with computational complexity of $O(\log nM(n))$ [16], where n denotes the number of digits of precision at which the function is to be evaluated, and $M(n)$ stands for the complexity of the chosen multiplication algorithm. By contrast, the computational complexity of confluent Hypergeometric function in [12] is $O((\log n)^2 M(n))$ [17]. On the other hand, even though the proposed expressions contain infinite sums as well, it can be shown that they converge to the exact value very quickly. Based on simulations, with the number of computed terms $N = 20 \sim 100$, the truncation error can achieve the double-precision accuracy.

C. Maximal Ratio Combining

Using MRC, multiple CRs directly amplify and forward the received signals, instead of the energy vectors, to the FC, where the data are combined by the MRC combiner. Then an energy detector measures the output of the MRC combiner. Therefore, the test statistic, Y^{mrc}, can be modeled by central and non-central chi-square distributed random variables as

$$Y^{mrc} \sim \begin{cases} \chi_{2u}^2, & H_0 \\ \chi_{2u}^2(2y_{mrc}), & H_1 \end{cases} \quad (21)$$

where $y_{mrc} = \sum_{i=1}^{L} y_i$ denotes the instantaneous SNR at the output of the MRC combiner [14].

Similarly, over AWGN channels, the probabilities of false alarm and detection can be calculated using (4), (6), and (21)

$$P_{fa}^{mrc} = \frac{\Gamma(u, \lambda/2)}{\Gamma(u)} \quad (22)$$

$$P_d^{mrc} = Q_u(\sqrt{2y_{mrc}}, \sqrt{\lambda}), = 1 - \sum_{n=0}^{\infty} \frac{\gamma(n+u, \frac{\lambda}{2})}{\Gamma(n+u)n!} y_{mrc}^n e^{-y_{mrc}}. \quad (23)$$

The PDF of the SNR, y_{mrc}, at the output of the MRC combiner is given by

$$f(y_{mrc}) = \frac{m^{Lm} y_{mrc}^{Lm-1}}{\overline{y}^{Lm} \Gamma(Lm)} e^{-\frac{m}{\overline{y}} y_{mrc}}, \quad y_{mrc} > 0 \quad (24)$$

Similarly to III-A, the average probability of detection can be calculated by averaging (23) over (24) and calculating the integral as

$$\overline{P_d^{mrc}} = 1 - B(u, Lm, L\overline{y}). \quad (25)$$

Compared with the result in [10], it is evident that the proposed expression in (25) is much simpler to compute.

D. Selection Combining

Under SC, the energy detector measures the output of the SC combiner. The test statistic, Y^{sc}, can be modeled by central and non-central chi-square distributed random variables as

$$Y^{sc} \sim \begin{cases} \chi_{2u}^2, & H_0 \\ \chi_{2u}^2(2y_{sc}), & H_1 \end{cases} \quad (26)$$

where $y_{sc} = \max(y_1, y_2, \cdots, y_L)$ denotes the instantaneous SNR at the output of the SC combiner [14]. In other words, rather than processing all fading branches, SC processes only one of the diversity branches with the highest SNR. Over AWGN channels, the probabilities of false alarm and detection can be calculated using (4), (6), and (26) by

$$P_{fa}^{sc} = \frac{\Gamma(u, \lambda/2)}{\Gamma(u)} \quad (27)$$

$$P_d^{sc} = Q_u(\sqrt{2y_{sc}}, \sqrt{\lambda}), = 1 - \sum_{n=0}^{\infty} \frac{\gamma(n+u, \frac{\lambda}{2})}{\Gamma(n+u)n!} y_{sc}^n e^{-y_{sc}}. \quad (28)$$

Over multiple i.i.d. Nakagami-m fading channels, if the fading factor m is restricted to an integer value, the PDF of y_{sc} can be obtained from the Appendix of [18] as

$$f(y_{sc}) = \frac{L}{\Gamma(m)} \sum_{l=0}^{L-1} (-1)^l \binom{L-1}{l} \sum_{k=0}^{l(m-1)} b_k^l \left(\frac{m}{\overline{y}}\right)^{m+k} \times y_{sc}^{m+k-1} e^{-\frac{m(l+1)}{\overline{y}} y_{sc}} \quad (29)$$

where b_k^l can be recursively computed as

$$b_0^l = 1, \quad b_1^l = l, \quad b_{(m-1)l}^l = \frac{1}{\Gamma(m)^l},$$
$$b_k^l = \frac{1}{k} \sum_{j=1}^{J} b_{k-j}^l \frac{j(l+1)-k}{j!} \quad (30)$$

with $J = \min(k, m-1)$, and $k \in [2, (m-1)l - 1]$.

The average probability of detection can be evaluated by averaging P_d^{sc} in (28) over the SNR distribution in (29) as

$$\overline{P_d^{sc}} = \int_0^\infty P_d^{sc}(y_{sc}, \lambda) f(y_{sc}) dy_{sc}, \quad y_{sc} > 0. \quad (31)$$

Substituting (28) and (29) into (31), we obtain

$$\overline{P_d^{sc}} = 1 - \frac{L}{\Gamma(m)} \sum_{l=0}^{L-1} (-1)^l \binom{L-1}{l} \sum_{k=0}^{l(m-1)} b_k^l \left(\frac{m}{\overline{y}}\right)^{m+k} \times \sum_{n=0}^{\infty} \frac{\gamma(n+u, \frac{\lambda}{2})}{\Gamma(n+u) n!} \int_0^\infty y^{n+m+k-1} e^{-\frac{m(l+1)+\overline{y}}{\overline{y}} y} dy. \quad (32)$$

Using (3.351-3) in [15] for calculating the integral in (32), we end up with

$$\overline{P_d^{sc}} = 1 - L \sum_{l=0}^{L-1} (-1)^l \binom{L-1}{l} \sum_{k=0}^{l(m-1)} b_k^l \left(\frac{m}{\overline{y}}\right)^{m+k} \times \sum_{n=0}^{\infty} \frac{\gamma(n+u, \frac{\lambda}{2})(m)_{n+k}}{\Gamma(n+u) n!} \left(\frac{\overline{y}}{m(l+1)+\overline{y}}\right)^{n+m+k} . \quad (33)$$

Similarly to the analysis SLC and SLS, we can find that the proposed formula in (33) has a lower computational complexity than the result in [11].

IV. Simulation Results

In simulations, we use complementary receiver operating characteristic (ROC, P_{fa} vs $1 - P_d$) curves to quantify the detection performance of energy detection. From both Fig. 2 and Fig. 3, we can see that all diversity reception schemes have sensing diversity gains, compared with the no-diversity case. In Fig. 2, we compare the detection performance of energy detection using MRC with that using SLC. It illustrates that, with the aid of full CSI, MRC outperforms SLC. Fig. 2 also shows that the detection performance becomes better when the local-mean SNR grows or the number of channels, L, increases. In Fig. 3, a similar phenomenon can be found that either a higher SNR or a larger L will result in a better detection performance. Fig. 3 also depicts that the SLS scheme is superior to the SC scheme. The reason behind this phenomenon is that, in comparison with choosing the branch with the highest SNR, selecting the branch with the largest energy to do the hypothesis test is more straightforward for improving detection performance. Moreover, both SLS and SC in Fig. 3 are inferior to MRC in Fig. 2.

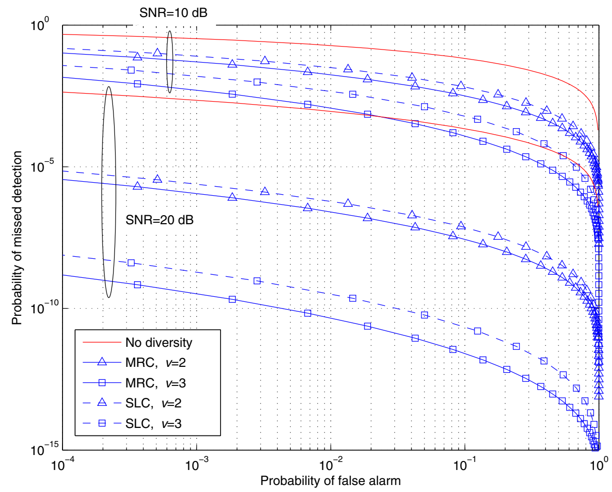

Fig. 2. Complementary ROC curves of the energy detection under MRC and SLC schemes, when the Nakagami fading factor $m = 3$, and the time bandwidth product $u = 1$.

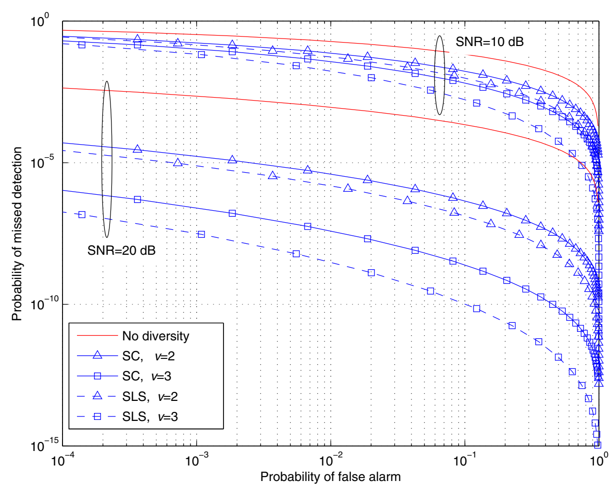

Fig. 3. Complementary ROC curves of the energy detection under SC and SLS schemes, when the Nakagami fading factor $m = 3$, and the time bandwidth product $u = 1$.

The Nakagami-m fading factor, m (also called shape factor), indicates the severity of fading and the quality of the channel. The severity of fading reduces when the fading factor, m, increases. The Nakagami-m fading model includes the Rayleigh fading ($m = 1$) as a special case. In the limit as $m \to \infty$, it converges to a non-fading channel. In Fig. 4, it is shown that the performance of diversity reception over Nakagami-m fading channels with $m = 3$ is much better than that over Rayleigh fading channels with $m = 1$. This is because the severity of fading for the former case is less than that of the latter case. It is manifest that using MRC we can obtain the best detection performance over both kinds of fading channels. For $m = 3$, MRC outperforms SLC, SLS, and SC by roughly

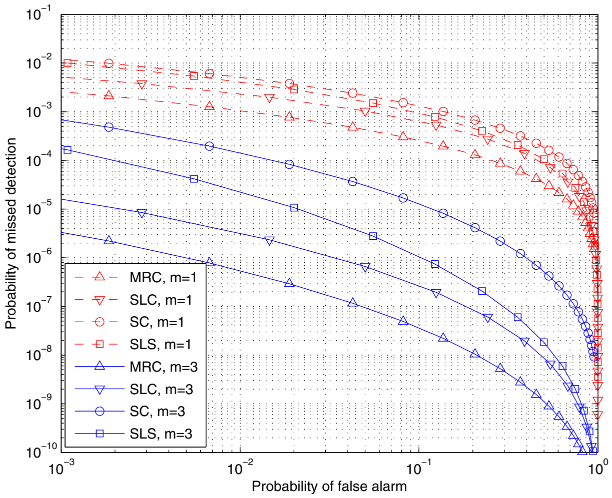

Fig. 4. Comparison of MRC, SLC, SC, and SLS, when the local-mean SNR $\overline{y} = 15$ dB, the number of collaborative CRs $L = 3$, and the time bandwidth product $u = 1$.

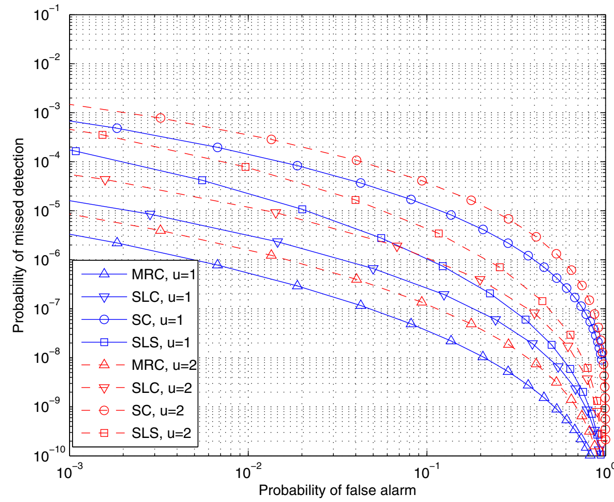

Fig. 5. Comparison of MRC, SLC, SC, and SLS, when the local-mean SNR $\overline{y} = 15$ dB, the number of collaborative CRs $L = 3$, and the Nakagami fading factor $m = 3$.

one, two, and three orders of magnitude on index $1 - P_d$, respectively. On the other hand, for Rayleigh fading channels ($m = 1$), the gain of MRC is less.

The parameter u denotes the time bandwidth product in the test statistic and is directly related to the DoF of the test statistic as shown in (2). In Fig. 5, we find that for a fixed probability of false alarm, e.g., $P_{fa} = 0.01$, the probability of missed detection decreases when u reduces. In addition, MRC is the best diversity reception scheme for both $u = 1$ and $u = 2$. In comparison to SLC, MRC has gains of approximately a half order of magnitude in $1 - P_d$, similar to the gain of SLC over SLS. It can also be observed that SLS has improvement compared with SC and the gain is roughly one order of magnitude.

V. Conclusions

In this paper, we have studied the performance of spectrum sensing using energy detection under different diversity reception schemes, i.e., MRC, SC, SLC, and SLS. It has been shown that the proposed expressions have lower computational complexity compared with those proposed in the literature. Since CR nodes are often restricted to limited computational resources, these computationally inexpensive expressions are advantageous. Additionally, we have compared the performance of different diversity reception schemes. With perfect CSI, MRC gives an upper bound of the detection performance. In the case where CSI is not available, SLC is a good choice as it has a better detection performance than SLS. Besides, MRC and SC require double transmission bandwidth compared with SLC and SLS, because they forward complex data instead of real data. Hence, where there is a restriction on the bandwidth of the control channel, SLC is preferred. With strict constraints on the bandwidth of the control channel, we should resort to decision fusion based collaborative spectrum sensing techniques. Future investigations may include decision fusion approaches for comparison.

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